Optik - International Journal for Light and Electron Optics 247 (2021) 167862

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.com/locate/ijleo

Original research article

Phase difference between electric and magnetic fields of the electromagnetic waves

M. Muhibbullah [1]

Department of Electrical and Electronic Engineering, Bangladesh University, 15/1, Iqbal Road, Mohammadpur, Dhaka 1207, Bangladesh

ARTICLE INFO

Keywords:
electromagnetic wave
phase difference
electromagnetic energy
continuous energy: near field
far field

ABSTRACT

The electromagnetic (EM) wave energy is a significant part of the different purposes in the science, technical and engineering sectors. The phase difference between electric and magnetic fields holds important roles to give clear conception of (i) the EM wave energy and (ii) the action process of light-electron interactions. Most of the researchers think that the phase difference between electric and magnetic fields of the EM waves is 0°. In this work, we have discussed in detail about the phase difference between the fields. We have shown that the phase difference between the fields is 90° for all types of EM wave radiations in the both forms i.e. descriptive and mathematical. The electric field is the driver of the EM wave power. The source of the EM wave makes a sinusoidal electric field continuously then the changing electric field makes a magnetic field instantly in all paths of its propagation, so the magnetic field is sinusoidal also with a delay phase. The simulation of this research work shows that the radiated energy density is sinusoidal and continuous. The research work may help to increase the applications of the EM radiations.

1. Introduction

The EM waves have been using in many applications of science, technical and engineering sectors such as telecommunications [1–3], photovoltaic [4–6], rectenna solar cell [7–9] light related sensors [10] etc. The calculation of the power and energy of the EM radiation is a useful part for all applications. The phase difference between electric and magnetic fields plays an important role to give actual value of power as well as energy of the EM waves; also, it gives clear conception about the action process of light-electron interactions. There are some powers and energies equations of the EM waves in society. James M. Hill et al. [11] have derived an equation for power density of the microwave. The power density equation has been given as;

$$Q = \frac{1}{2}\omega\varepsilon' E^2 \left(\mathrm{Watt}/\mathrm{m}^3\right), \tag{1}$$

where, $\varepsilon' = \frac{\sigma}{\omega}$, σ is electric conductivity, ω is angular frequency and E is electric field intensity. Shinobu Tokumaru [12] has derived an equation for energy density. The equation is

$$W_c = \frac{\delta\left(\omega\sqrt{\varepsilon\mu}\right)}{\delta\omega}\frac{EH^*}{2}\left(\mathrm{Joule}\Big/\mathrm{m}^3\right), \tag{2}$$

E-mail address: m.muhibbullah@bu.edu.bd.
[1] ORCID: 0000-0002-6601-9586.

https://doi.org/10.1016/j.ijleo.2021.167862
Received 26 July 2021; Accepted 19 August 2021
Available online 21 August 2021

where ε is electric permittivity, μ is magnetic permeability and H^* is a complex conjugate of the magnetic field. Andrzej Wolski [13] has stated an energy density equation of the EM waves. The equation is as follows

$$U = \frac{1}{2}\varepsilon_o E_o^2 (\text{Joule}/\text{m}^3), \tag{3}$$

here, ε_o is electric permittivity in vacuum and E_o is the maximum value of the periodic electric field. Andrzej Wolski [13] has also derived a power equation. The power equation is

$$P = \frac{(I_o l)^2 k^2}{12\pi\varepsilon_o C}(\text{Watt}) \tag{4}$$

Here, I_o is current amplitude and l is length of current and $k\left(=\frac{2\pi f}{C}\right)$ is wave vector. C is speed and f is frequency of the EM waves. The Poynting vector [14,15] is used as the power density of the EM waves. The power density equation is as follows

$$\vec{P} = \vec{E}\times\vec{H}(\text{Watt}/\text{m}^2), \tag{5}$$

where, $\vec{E}$ and $\vec{H}$ are sinusoidal electric and magnetic fields respectively. To establish and use all of the above equations, the phase difference between electric and magnetic fields has not been considered. Maxwell [16] has proved mathematically that the electric field, magnetic field and propagation direction of the EM waves are orthogonal. The phase difference between the fields is not clear in his explanation. Hertz [17] has shown that the phase difference of the EM radiation is 90° near the source of the EM waves. There are some more research works [18–20] on propagating EM waves, in which the researchers have considered that the phase difference between the fields is 90° near the field source (it looks as Fig. 1(a)). As their concept, the phase difference decreases with distance, and finally it becomes 0° in far distance (as Fig. 1(b)). The theoretical works have been done hypothetically. Recently Muhibbullah et al. [21] have derived frequency dependence power and energy density equations, which can calculate power and energy density from EM wave radiation. They consider that the phase difference is 90° during derivation, but after derivation, they have not given emphasis on the phase difference. Their power density equation is

$$P_D = 4\pi^2\varepsilon_o\mu_o f^2\vec{E}\times\vec{H}.\vec{S} \quad (\text{Watt}/\text{m}^2), \tag{6}$$

Here f is frequency, ε_0 and μ_0 are constants of the medium, $\vec{S}$ is the area of the irradiated space, $\vec{E}$ and $\vec{H}$ are instant electric and magnetic fields at a place, respectively. Muhibbullah et al. [22–24] have used the power density equation of the reference [21] to explain the photoelectric effect in which they have considered that the phase difference between electric and magnetic fields is 90°. The explanation has matched smoothly with the experimental results. Very recently Muhibbullah et al. [3] have derived a power equation of a monopole receiving antenna. They have considered 90° phase difference between the fields also. Their power equation matches with the practical results. In the present study, we have explained the phase difference between electric and magnetic fields for all spectrums of EM wave radiation. We have given explanations about the phase difference between the fields in the form of descriptive and mathematical. We have given a simulation result of the power density of the EM wave radiation versus time for two phase-differences also.

2. Theoretical explanation

According to Maxwell's propagating EM wave theory, the electric field, magnetic field and propagating direction are orthogonal [13,16,25]. It is true for all types of EM radiations such as plane polarized, circular polarized and non-polarized EM radiations including visible light, ultraviolet radiation, X-ray, Gamma ray etc. The phase difference between electric and magnetic fields has been discussed step by step. Firstly, the phase difference of the low frequency EM wave radiation and then the high frequency EM wave radiation have been stated, after then the mathematical expression of that has been given as sub-sections.

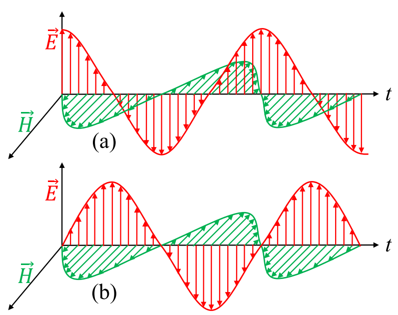

Fig. 1. Plane polarized EM waves with different phase differences (θ) between the electric and magnetic fields (a) $\theta = 90°$ and (b) $\theta = 0°$.

2.1. Descriptive

2.1.1. EM waves of low frequency

Usually the electronic device produces low frequency EM wave radiation. Let us consider an LC circuit with a negligible ohmic resistance. The second order differential equations of charge Q or current I can be derived easily [26] with respect to time, t. The stored electric and magnetic [27] energy have been exchanged periodically between capacitor and inductor in the circuit. The differential equations of the charge and current can be written as;

$$\frac{d^2Q}{dt^2} + \frac{1}{LC}Q = 0, \tag{7}$$

and,

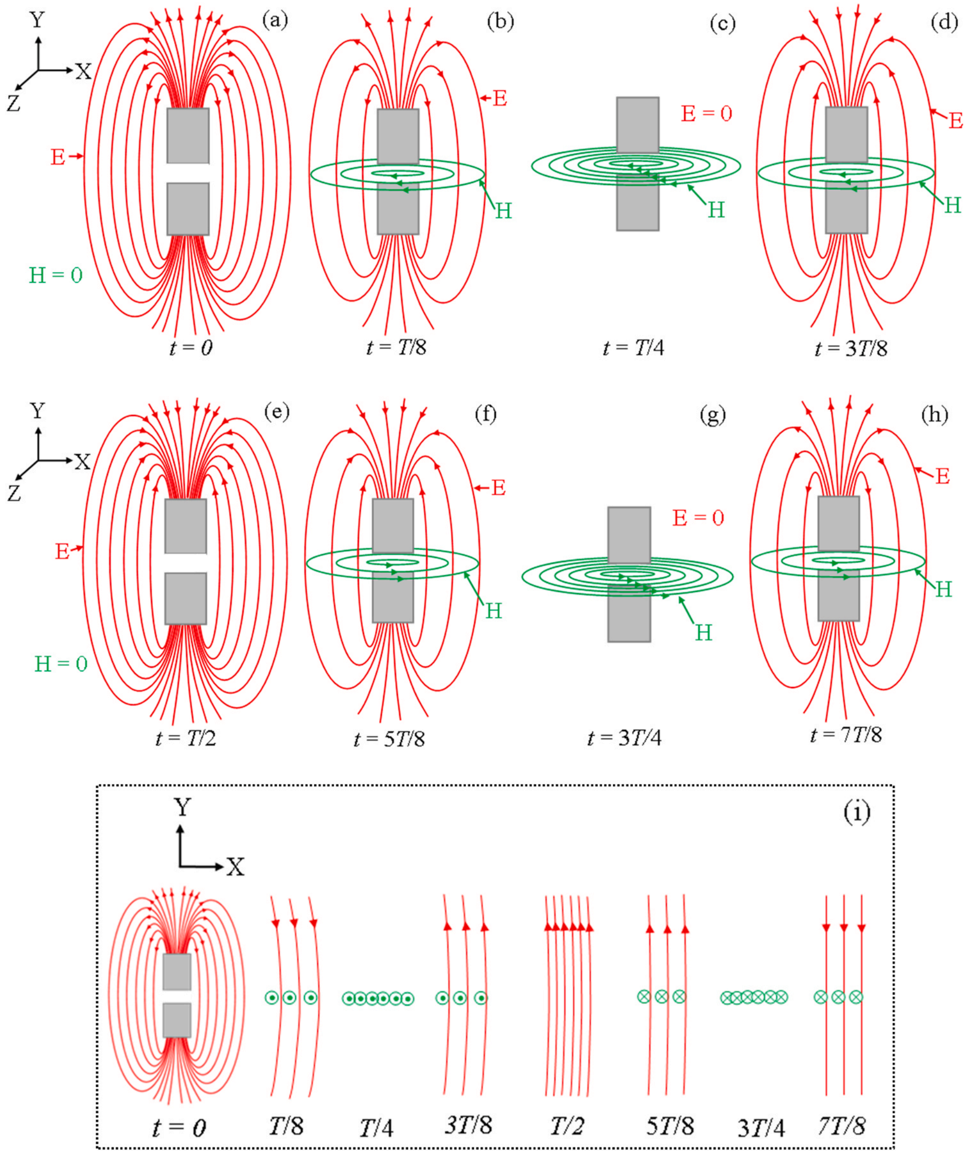

Fig. 2. Dipole antenna with electromagnetic wave radiation. The figures are the instant images of the electric (red, XY plane) and magnetic (green, XZ plane) fields at a moment in the near and far distances. (a) At the initial moment $t = 0$, (b) at a moment of one eighth value of time period, $t = T/8$, (c) at $t = T/4$, (d) at $t = 3\ T/8$, (e) at $t = T/2$, (f) at $t = 5\ T/8$, (g) at $t = 3\ T/4$ and (h) at $t = 7\ T/8$. And, the figure (i) represents instant images of the EM fields at different moments in different distances. The dot and cross signs represent outward and inward magnetic fields respectively. For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.

$$\frac{d^2I}{dt^2}+\frac{1}{LC}I=0. \tag{8}$$

Here, L is self-inductance of the inductor and C is capacitance of the capacitor. In this way, the system radiates EM waves with frequency f ($\omega = 2\pi f = 1/\sqrt{(LC)}$) around the circuit. The Eqs. (7) and (8) look similar, but the natures of the values of "Q" and "I" are not same at a moment according to the device activity. When one is maximal (or upward) at that time the other is minimal (or downward). Then the solution of the two equations should not be exactly the same. The current flowing is not possible initially without any charge in the capacitor or any bias in the circuit. So we have considered that the initial current is zero and the capacitor is fully charged (Q_o). During the oscillation of charge and current, one is increased and other is decreased at a moment, and vice versa. Thus, the solutions of differential equations should be as

$$Q(t)=Q_o\cos\omega t, \tag{9}$$

and,

$$I(t)=I_o\sin\omega t. \tag{10}$$

Here Q_o is the maximum value of charge, Q and I_o is the maximum value of current, I. The electric field $\vec{E}(\vec{r},t)$ is proportional to the charge, Q, and the magnetic field $\vec{H}(\vec{r},t)$ is proportional to the current, I. Then according to the Eqs. (9) and (10) the electric field and magnetic field can be written at a place $\vec{r}$ (distance from the circuit) as;

$$\vec{E}(\vec{r},t)=\vec{E}_o(\vec{r})\cos\omega t, \tag{11}$$

and,

$$\vec{H}(\vec{r},t)=\vec{H}_o(\vec{r})\sin\omega t,$$

or,

$$\vec{H}(\vec{r},t)=\vec{H}_o(\vec{r})\cos\left(\omega t-\frac{\pi}{2}\right) \tag{12}$$

Here, $\vec{E}_o(\vec{r})$ and $\vec{H}_o(\vec{r})$ are maximum values of electric and magnetic fields nearby of the circuit, respectively. Since the charge as well as the electric field initiates to create EM waves, the magnetic field is behind the electric field. The Eqs. (11) and (12) indicate that the phase difference between electric field and magnetic field is 90° in case of low frequency EM radiation. On other hand, usually an electronic device radiates EM waves in air by an antenna. Fig. 2 illustrates the radiation pattern of the EM waves for a dipole antenna for an oscillating electric power. The oscillating electric charge of the dipole antenna makes an oscillating electric field in the surrounding three dimensionally. Impact of changing electric fields produces an oscillating magnetic field [16] in the three dimensions also. To avoid complexity, the electric field (red line) has been shown to XY plane only and the magnetic field (green line) has been shown to ZX plane only. The antenna makes the line of electric field as a loop. The value of the line density changes as sinusoidal with time. The direction of the electric field remains along the positive direction of Y-axis (Fig. 2(a-c)) during the quarter time period of an oscillation. In this time, the line density starts to decrease from a maximum value to the zero, then starts to increase up to the maximum (Fig. 2(c-e)) with negative direction. Then, the line density starts to decrease from the maximum value to zero without changing direction (Fig. 2(e-g)), then, it increases with changing direction (Fig. 2(g-h)). A portion of the loop of electric field remains inside the dipole up to quarter period with varying density. Then the field disappears for a moment and generates again with the opposite direction as the loop. This repetition work continues continuously with time. The ends of the line of released electric field remain open. The lines cannot make a loop with the next (other) opposite lines of the electric field after release because there is a time interval (distance) between opposite lines. There is no opportunity to travel as a full loop of electric field from the antenna. Few researchers show the electric field as a loop (see the figure 5 of reference [28]). If the field is able to make a loop then the field should be vanished within a short time by the law of electric line of force as well as field because the line of electric field tries to be shortest always. Then the similar oriented parallel lines of electric field travel without making a loop, and the end of two lines is closer for the near field. The distance of the ends of two lines is wider for the far field (Fig. 2(i)) because the lines become parallel in the far distance. Fig. 2 clearly demonstrates that when the electric field is maxima then the magnetic field is zero and vice versa. The nature of the density of the magnetic field is similar to the nature of the electric field but their phase is different. The figure indicates that the phase difference between electric and magnetic fields is 90°. This expression agrees with previous report [17–20] for the case of near field. The researchers [18–20] report that the phase difference is 0° for the far field. They have taken this decision from a complex expanded series hypothetically. However, Fig. 2 reveals that the phase difference of the EM waves is 90° for both near and far distances. Because the source device does not do any extra work for the far field; that means the source device action is same for both near and far fields. Moreover, there is no theory of physics to support the change of phase difference from 90° to 0°. Therefore, an observer of far distance must observe the 90° phase difference between electric and magnetic fields as the near field. A research group [3] has derived a power equation of a monopole-receiving antenna. They have considered the 90° phase difference between the fields of the EM waves. Their power equation matches with the practical results smoothly.

2.1.2. EM wave of high frequency

The electron transition of the atomic orbit produces infrared, visible and ultraviolet light, X-ray and gamma ray. These EM radiations contain very high frequencies. As we said in the previous subsection, that the electric field initiates EM radiation according to the action of the EM wave source in the case of microwaves. The movement of the electric charge as well as the changing electric field produces magnetic fields. The electric field can exist without any effect of the magnetic field, which means the electric field is able to appear without magnetic field, i.e. the electric field is independent. It indicates that to produce any type of the EM wave radiation the electric field acts as a dominator and the magnetic field is generated by action of the electric field [16]. So, their phases should not be the same in the EM waves. Very recently, a researchers group [29] presented in an international conference how an EM wave transits the electron from inner orbits. They consider 90° phase difference between the fields of light energy and then the light rotates orbital electrons in the inner orbits. Then a pair (rotated) excited electrons of equal (absorbed) energy but opposite spinning achieves repulsive EM force. The electrons pair is removed from the orbit if the achieved energy is larger enough than the orbital binding energy. Recently Muhibbullah et al. [22–24] have explained the photoelectric effect in which they have considered that the phase difference between electric and magnetic fields is 90°. The explanation has matched smoothly with the experimental results. Moreover, the natures of microwave and other EM radiations (infrared, visible light, ultra-violet, X-ray and Gama ray) are similar such as reflection, refraction, interference, diffraction, polarization, speed etc. Only their frequency is different. Then we can say that the phase difference between the fields of EM radiation should be similar to the microwave that is 90°.

2.2. Mathematical

Maxwell's propagating EM field theory states that the directions of electric field, magnetic field and EM wave propagation are orthogonal. Also, Maxwell's theory reveals that the changing electric field produces a magnetic field [16] and vice versa. According to Maxwell's field equations, it should be logical to state that the produced instant magnetic field is proportional to the changing rate of electric field. Ampere's law and Biot Savart law support the logic. Mathematically the relation between the instant magnetic field and the changing rate of electric field with time can be written as;

$$\vec{H}(\vec{r},t) \propto \frac{d\vec{E}(\vec{r},t)\times\hat{r}}{dt},$$

or,

$$\vec{H}(\vec{r},t) = k\frac{d\vec{E}(\vec{r},t)\times\hat{r}}{dt}. \tag{13}$$

Here, the k is the proportionality constant and $\hat{r}$ is the unit vector along the propagation direction. The unit vector, $\hat{r}$, has been taken to make sure the perpendicular direction of magnetic field with electric field because of Maxwell's field theory. For a place, the unit vector is constant with time. Putting the value of electric field from Eq. (11) into Eq. (13), and derivative then we get;

$$\vec{H}(\vec{r},t) = -\omega k\vec{E}_o(\vec{r})\times\hat{r}\sin\omega t,$$

or,

$$\vec{H}(\vec{r},t) = -\omega k\vec{E}_o(\vec{r})\times\hat{r}\cos\left(\omega t - \frac{\pi}{2}\right) \tag{14}$$

The minus sign indicates the direction of the produced instant magnetic field. In the sinusoidal electric field, the value of it changes with time and the direction of the electric field changes after half time periods. Thus, in the negative changing rate of electric field, the magnetic field becomes a positive sign. The $\vec{E}_o\times\hat{r}$ is the vector quantity and acts along the direction of the magnetic field and its value is constant with time at a place. Then, for a monochromatic EM wave, $\omega k\vec{E}_o(\vec{r})\times\hat{r}$ should be a constant and it can be treated as the amplitude of the magnetic field $\vec{H}_o(\vec{r})$. So, the Eq. (14) becomes similar to Eq. (12). Then the Eqs. (11) and (14) indicate that the phase difference between the (electric and magnetic) fields is 90° as we said in previous. On other hand, Fig. 3 explains the mathematical expression clearly. The changing electric field as a sinusoidal mode of the EM waves with time is shown in Fig. 3. We have to explain that for a change of the electric field, how much instant value of magnetic field produced? In this way, we can estimate the phase

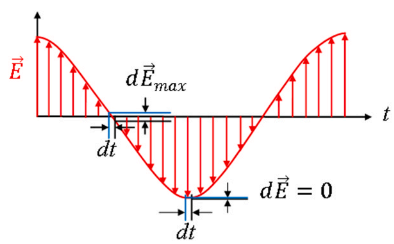

Fig. 3. The changing rate of electric field with time in the propagating EM wave.

difference between the fields. Let us consider that the sinusoidal electric field is situated as a static field on a time frame instead of time dependent value at a place. Fig. 3 shows that the change rate of electric field with time is zero at around the peak region. Then, the magnetic field should have disappeared at that time as Maxwell's dynamic field theory [16]. In the front or back time region of the peak, the change rate of the electric field is larger. In the region of absolute zero value of electric field, the change rate of the electric field is maxima, so the instant magnetic field at this moment must be maxima according to the field theory. Therefore, when the absolute value of the electric field is minima at that moment, the produced instant magnetic field is maxima for the maximum changing rate of the electric field. When the absolute value of the electric field is maxima then, at that moment, the produced instant magnetic field is minimal. The fact indicates clearly that the phase difference between electric and magnetic fields is 90°. These interactions between electric and magnetic fields continue up to the end (in all distances) of the propagated EM radiation. The information is very important because we can decide from this that the phase difference is 90° not only for the near field but also for the far field. The electric field is the driver of the EM wave power; the source of the EM wave makes a sinusoidal electric field continuously then the changing electric field makes a magnetic field instantly in all paths of its propagation without depending on any distance. Some researchers [18–20] reported that the phase difference is 0° for a far field. Maxwell's dynamic field theory does not support the 0° phase difference. For example- if we consider that the phase difference is 0°, in that case, when the absolute value of magnetic field is minima then the absolute value of electric field is also minima, but at that moment, the change rate of electric field is maxima (as Fig. 1(b)). The concept violates the dynamic field theory, because, when the magnetic field is minimal, at that moment, the change rate of electric field must be minima as Maxwell's theory. C. Capps [30] reported using the expansion equation of SK Schelkunoff that the $1/r^3$ terms dominate their expansion equation for the near field. As the distance (r) increases, the$1/r^3$ and $1/r^2$ terms attenuate rapidly and, as a result, the $1/r$ term dominates in the far field as in his report. They have not proved the mathematical (different type of inverse proportions) concept by the theory of physics or by experiment. Their idea comes from a hypothetical algebraic concept. The concept is not reliable because an EM wave power spread following with different rules in an incident. Rather than it is well known that the light intensity is inversely proportional to the square of the distance [31] between detector and light source. Many researchers [31–33] have proved experimentally the inversely proportional to the square of the distance. The hypothetical concept of mathematics does not match sometimes with the theory of physics. Therefore, their [18–20,30] hypothetical idea is going to be replaced by the modern connect [3,21–24] of the EM wave theory.

3. Simulation and discussions

In the EM wave radiation, both the electric and magnetic fields are sinusoidal with time. The electric field is the main power of the EM wave radiation. The magnetic field is dependent and it is produced by changing electric fields. From Eq. (6) the flow of power density of the EM wave can be written [20] as

$$P_D = 4\pi^2 \varepsilon_o \mu_o f^2 EHS \quad . \tag{15}$$

Here E and H are perpendicular to each other. We consider that the EM wave radiation has fallen perpendicularly on the plane surface S, so the direction of the EM wave propagation and the direction of the surface is same. We have considered and proved that the phase difference between electric and magnetic fields is 90°, however we reconsider that the phase difference is θ here. The value of the θ can be either 0° or 90° for present believing and our concept. Considering the modulus of $\vec{E}$ and $\vec{H}$ of the Eqs. (11) and (12) and putting the values of the E and H into Eq. (15), and we get,

$$P_D = 4\pi^2 \varepsilon_o \mu_o f^2 S E_o H_o \cos\omega t \cos(\omega t - \theta). \tag{16}$$

To plot the power density P_D of the EM wave radiation for two different phase differences, let us consider the value of $(4\pi^2 \varepsilon_o \mu_o f^2 S)$ is 1. Some values of ωt ($T/16$, $2T/16$, $3T/16$, ..., T) have been used to find P_D from Eq. (16) for the phase differences 0° and 90°. We have plotted the values of P_D and ωt for a constant energetic EM wave radiation as graph in Fig. 4. The figure shows that the power density is all time positive when the phase difference is 0° and the power density is sinusoidal when the phase difference is 90°. A researcher [18] commented that "if the electric and magnetic fields are phase synchronous (0°), then when one is positive, the other is positive and when one is negative the other is negative. In either case, the Poynting flux is always positive and there is always an outflow of energy. If the electric and magnetic fields are in phase of 90°, then half the time the fields have the same sign and half the

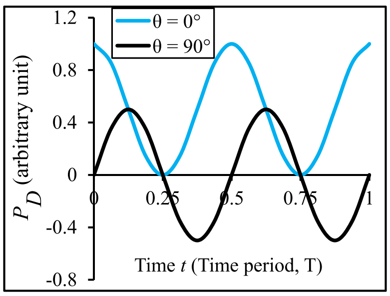

Fig. 4. The simulated results of power density with time for phase differences 90° and 0°.

time the fields have opposite signs. Thus, half the time the Poynting vector is positive and represents outward energy flow and half the time the Poynting vector is negative and represents inward energy flow. Thus, fields in phase are associated with far field radiation and fields of 90° phase are associated with near field." Our simulated results of the power density of the EM waves for both phase differences agree exactly with the expectation of the reporter. However, his statement about the process of the power flow for far EM waves is not clear, because there is no supporting logic as to why the power flow will be different for the far field than the bear field. According to their [18–20] reports, the power of the near field is both outward and inward, and at that region, the EM radiation is overcome the limit of near field distance. No problem is raised to propagate from source to the distance of near field limit. It reveals that by the process 'outward and inward', the energy flow is possible. We showed that the phase difference between electric and magnetic fields is 90° already, therefore, the EM wave power propagates with positive and negative value in each cycle. It is well known to all that in the AC electric power system, the carriers (electrons) move front and back per cycle and the electric power proceeds from one city to another by sinusoidal oscillation of the carriers. Therefore, we can say that the EM wave power propagates as the form of sinusoidal continuously.

4. Conclusions

The energy fluctuation of the EM waves depends on the phase difference between electric and magnetic fields. We have presented the phase difference between the fields theoretically here. In the case of low frequency EM waves, we have shown that the phase difference between the fields is 90° considering the action of the source device of the EM waves. Mathematical expression also shows that the difference is 90° for both near and far fields. The electric field is the driver of the EM wave power. The source of the EM waves makes a sinusoidal electric field continuously then the changing electric field makes magnetic field instantly in all paths of its propagation. The simulation of this research work shows that the power density of the EM wave flow as the form of sinusoidal with 90° the phase difference between electric and magnetic fields. The research work may help to increase the applications of the EM wave radiations. The "interaction of free electrons under light" and the "orbital transition of electrons" based on the EM wave concept are our future research works.

Declaration of Competing Interest

I have no conflict of any financial or other interest.

Acknowledgements

The author is grateful to Professor Hiro Munekata of the Institute of Innovative Research, Tokyo Institute of Technology, Japan, for his useful discussions and comments, which have been helpful to write this paper.

References

[1] T.A. Milligan, Modern Antenna Design, second ed., IEEE Press, Wiley-Interscience, John Wiley & Sons, Inc, 2005.
[2] R.T. Johnk, Motohisa Kanda, Alternative contour technique for the efficient computation of the effective length of an antenna, IEEE Trans. Antennas Propag. 42 (5) (1994) 747–749.
[3] M. Muhibbullah, Jamal Q. Almarashi, Haleem Ashraf, M. Abdel, El-Zohary Salah, Theoretical and experimental investigations on optimization of the received power of a monopole antenna, Phys. Scr. 96 (2021), 015502.
[4] M. Muhibbullah, M. Ichimura, Fabrication of heterojunctions based on chemically deposited copper oxide thin films for solar cell application, Trans. Mater. Res. Soc. Jpn. 36 (2) (2011) 195–198.
[5] M. Muhibbullah, M. Ichimura, Fabrication of copper oxide thin films by the drop chemical deposition technique, Mater. Res. Bull. 47 (2012) 1968–1972.
[6] B.P. Rai, Cu_2O solar cells: a review, Sol. Cells 25 (1988) 265–272.
[7] A.S. Sharma, Virendra Singh, Thomas L. Bougher, A. Cola Baratunde, A carbon nanotube optical rectenna, Nat. Nanotechnol. 10 (2015) 1027–1032.
[8] G. Moddel, Optical rectennas: nanotubes circumvent trade-offs, Nat. Nanotechnol. 10 (2015) 1009–1010.
[9] B.J. Eliasson and Garret Moddel, US, Patent 6534784 B2, 2003.
[10] Derci Felix da Silva, Daniel Acosta-Avalos, Light dependent resistance as a sensor in spectroscopy setups using pulsed light and compared with electret microphones, Sensors 6 (2006) 514–525.
[11] James M. Hill, Michael J. Jennings, Formulation of model equations for heating by microwave radiation, Appl. Math. Modelling 17 (7) (1993) 369–370, https://doi.org/10.1016/0307-904X(93)90061-K.
[12] Shinobu Tokumaru, Electronics and Communications in Japan, Part 1 74(9) (1991), Translated from Denshi Joho Tsusbin Gakkai Ronbunshi 73-B-II(12) (1990) 905.
[13] Andrzej Wolski, Theory of Electromagnetic Fields, University of Liverpool, and the Cockcroft Institute, UK, arXiv:1111.4354v2 [physics.acc-ph] 27 Oct 2014.
[14] Gupta Dr SL, Kumar Dr V. and Sing Dr SP. Electrodynamics, ninth ed., Pragati Prakashan, Begum Bridge, Meerat, India; Printed by Raj Printers, Meerat, India, 1990.
[15] Bo Thidé, Electromagnetic Field Theory, Department of Astronomy and Space Physics, version released 20th January, Uppsala University, Sweden, 2004.
[16] Maxwell J. Clerk, Philos. Trans. R. Soc. Lond. 155 (1865) 459.
[17] Heinrich Hertz, in: D.E. Jones (Ed.), Electric Waves, Dover Publications Inc, New York, 1962.
[18] Hans Gregory Schantz, 2005 IEEE Antennas and Propagation Society International Symposium, Washington, DC, USA, 3B, 3–8 (2005) 134.
[19] Saifullah Amin, Bilal Ahmed, Muhammad Amin, Muhammad Inam Abbasi, Adnan Elahi, Usman Aftab, Establishment of boundaries for near-field, fresnel and fraunhofer-field regions, in: Proceeding of 2017 Asia Pacific Microwave Conference, paper id: 978-1-5386–0640-7/17$31.00©2017IEEE, pp. 57–60.
[20] H.G. Schantz, Theory and practice of near-field electromagnetic ranging, in: Proceedings of the 2012 International Technical Meeting of The Institute of Navigation, January 30 - 1, 2012, pp. 978–1013.
[21] M. Muhibbullah, A.M.A. Haleem, Y. Ikuma, Frequency dependent power and energy flux density equations of the electromagnetic wave, Results Phys. 7 (2017) 435–439.
[22] M. Muhibbullah, Y. Ikuma, Photoelectron ejection by electromagnetic wave, Optik 181 (2019) 802–809.

[23] M. Muhibbullah, Y. Ikuma, Refutation of the short report "On the impossibility of "Photoelectron ejection by electromagnetic wave", Optik 202 (2020), 163734.
[24] M. Muhibbullah, Y. Ikuma, Ejection angle and depth of photoelectron based on electromagnetic wave, J. Mod. Opt. 68 (16) (2021) 878–885.
[25] Dipak L. Sengupta, Tapan K. Sarkar, Maxwell, Hertz, the Maxwellians, and the early history of electromagnetic waves, IEEE Antennas Propag. Mag. 45 (2) (2003) 13–19.
[26] David Halliday, Robert Resnick and Jearl Walker, Fundamentals of Physics. Extended fifth ed., John Wiley and Sons (Asia) Inc, New York, Printed and bound in India by Thomson Press (India) Ltd, 1997.
[27] Hao Yu, Lei He, A provably passive and cost-efficient model for inductive interconnects, IEEE Trans. Comput. Aided Des. Integr. Circuits Syst. 24 (8) (2005) 1283–1294.
[28] Kemal Dervić, Vladimir Šinik, Željko Despotović, Basics of electromagnetic radiation, in: Proceedings of the IX International Conference Industrial Engineering and Environmental Protection 2019 (IIZS 2019) October 3rd-4th, 2019, Zrenjanin, Serbia, pp. 512–520.
[29] M. Muhibbullah , Yasuro Ikuma, Electromagnetic wave ejects the inner orbital electron of atom, in: Presented to the International Conference on Physics – 2020, 05–07 March, 2020; Atomic Energy Centre, Dhaka, Bangladesh, Organized by Bangladesh Physical Society. Poster number: PP – 108.
[30] C. Capps, Edn -Boston then Denver then Highlands Ranch Co- 46(18) (2001) 95.
[31] I. Sriyanti, P. Aliyana, L. Marlina , J. Jauhari, J. Phys.: Conf. Series. 1467 (2020) 012056.
[32] W. Setya, A. Ramadhana, H. Restu Putri, A. Santoso, A. Malik and M.M. Chusni, J. Phys. Conf. Ser., 1402 (2019) 044102.
[33] Z. Radzi, N.H. Abu Kasim, N.A. Yahya, N.A. Abu Osman, N.L. Kassim, Annals of Dentistry, 15, University of Malaya, 2008, p. 33.